PAPER

Performance Analysis of Source-Destination ARQ Scheme for Multiroute Coding in Wireless Multihop Networks

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SUMMARY For reducing bit errors on wireless channels, we have proposed the multiroute coding scheme on multiple routes for wireless multihop networks. In this paper, we introduce ARQ to our multiroute coding scheme. In our multiroute coding scheme, a destination node combines and decodes subpackets which are encoded and divided by a source node. Each intermediate node relays a subpacket, that is, only a part of a packet. Therefore, intermediate nodes cannot detect packet errors, and only a destination node can do so after combining and decoding subpackets. We propose an ARQ scheme between a source node and a destination node. We analyze the proposed ARQ scheme and evaluate the system performance.
key words: *wireless multihop network, multiple routes, ARQ, error correcting*

1. Introduction

Wireless multihop networks have been drawing much attention for the future generation mobile communication systems, mobile ad-hoc networks, and sensor networks [1]–[4]. In wireless multihop networks, a packet is transmitted from a source node to a destination node via intermediate nodes. These networks can be constructed flexibly by selecting various combinations of intermediate nodes. So, they can also establish multiple routes by using the multi-path routing [5], [6].

For reducing bit errors on wireless channels, we have proposed the multiroute coding scheme on multiple routes [7]. In our multiroute coding scheme, a transmitter at a source node encodes a packet, divides it into subpackets, and transmits them to the next nodes on multiple routes. Each intermediate node relays a subpacket to a destination node. A receiver at a destination node combines the received subpackets, and decodes them to get coding and diversity gain. We evaluated the performance of our multiroute coding scheme, and clarified it could improve the packet error rate.

In this paper, we introduce ARQ to our multiroute coding scheme. In our multiroute coding scheme, a destination node combines and decodes subpackets which are encoded and divided by a source node. Intermediate nodes relay a subpacket, that is, only a part of a packet. Therefore, intermediate nodes cannot detect packet errors, and only a destination node can do so after combining and decoding subpackets.

Then, we propose an ARQ scheme between a source node and a destination node for our multiroute coding scheme in wireless multihop networks. In this scheme, error detection is performed at a destination node. If errors are detected, a destination node returns a NACK message to a source node. A source node retransmits subpackets after receiving a NACK message. In contrast to single hop transmission, the subpacket transmission delay on each route is random variable in multihop networks [8]. The arrival time of a subpacket on each route is different. To reduce the delay time, which is defined as the elapsed time from the occurrence of a transmission request until its successful transmission, a destination node decodes and error-detects subpackets every time a subpacket arrives. However, if a NACK message is returned every time, unnecessary subpackets are retransmitted, and they result in the traffic jam. To avoid it, we introduce to adjust the timing to return a NACK message. The proposed ARQ scheme is analyzed by introducing the queueing model [8] and a trellis diagram. We also evaluate the system performance and clarify the effectiveness of the proposed ARQ scheme.

2. Multiroute Coding

In our multiroute coding scheme, we can employ the several types of error correcting codes [7]–[9]. Although the proposed ARQ scheme can be applied to all of them, in this section, we explain the multiroute coding scheme based on a turbo code [7].

2.1 Network Model

A wireless multihop network model is shown in Fig. 1. A packet is transmitted from a source node to a destination node via this network. By using a certain routing algorithm, N routes are established. Any two routes which exist between the same source and destination nodes have no common node or wireless link. On the other hand, two routes which exist between different source-destination pairs can have common nodes or wireless links. The number of hops from a source node to a destination node on the nth route is denoted by M_n. In each hop, a subpacket transmission is according to a certain access control protocol such as IEEE

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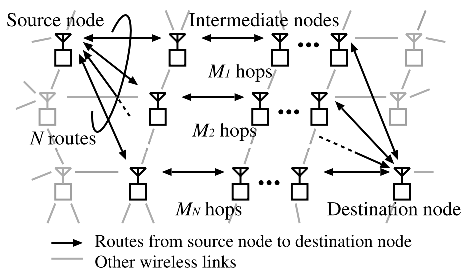


Fig. 1 Wireless multihop network model.

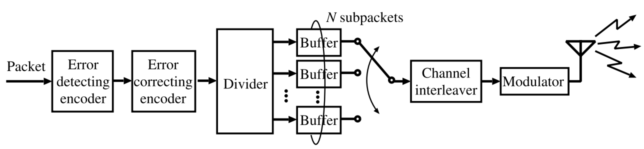


Fig. 2 Transmitter structure of a source node.

802.11. So the subpacket transmission delay is considered as not only the propagation delay but also the waiting time delay by the access control protocol.

2.2 Transmitter Structure of a Source Node

Figure 2 shows a transmitter structure of a source node. A bit sequence of a packet is encoded by error detecting and error correcting codes with a coding rate R_c. The encoded bit sequence is divided into N subpackets for multiple routes, and stored at buffers. Note that the encoded bit sequence of the turbo code consists of a message sequence and parity sequences, and the message sequence is more important than the parity sequences [10]. When the turbo code is used as the error correcting code, the message sequence is spread uniformly on subpackets so as to enhance the diversity effect [7]. Against the influence of time-variant fading, a channel interleaver for subpackets is employed. Each stored subpacket is interleaved, and after modulation, it is transmitted to the next node on the nth route. This operation is repeated until all subpackets are transmitted to the next nodes on N routes.

2.3 Regenerative Relay of an Intermediate Node

Intermediate nodes perform only the regenerative relay. At intermediate nodes, the received signal is demodulated to the hard-valued binary sequence, remodulated, and transmitted to the next node. Note that error correcting or error detecting are not performed at intermediate nodes.

2.4 Receiver Structure of a Destination Node

After M_n hops, a subpacket arrives at a destination node. A receiver structure of a destination node is shown in Fig. 3. The received signal via the nth route is demodulated, hard-decided and deinterleaved to the estimated bit sequence of a subpacket. It is stored at the buffer. Upon the arrival of a subpacket at a destination node, subpackets stored at buffers are combined, reordered by a combiner, and decoded to the bit sequence of the recovered packet by an error correcting decoder. If the subpacket on the nth route does not arrive at a destination node, the estimated bit sequence of it is assumed to be an all-zero sequence. The recovered packet is error-detected, and an ACK/NACK message is returned to a source node. The detail of the ARQ procedure is described in Sect. 3.

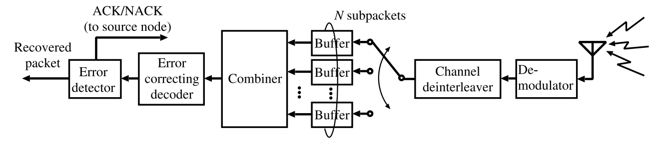


Fig. 3 Receiver structure of a destination node.

3. Source-Destination ARQ

As mentioned in Sect. 1, the arrival time of a subpacket on each route is different. Of course, it is possible to decode subpackets after receiving all N subpackets. But, to reduce the delay time, a destination node decodes subpackets arriving before and error-detects them every time a subpacket arrives. Then, an ACK message is returned when errors are not detected. Note that a NACK message does not have to be returned every error detection. If it is returned every time, unnecessary subpackets are retransmitted since subpacket retransmissions cannot be cancelled before an ACK message arrives at a source node (Fig. 4(a)). On the other hand, to decrease unnecessary subpacket transmissions, if a NACK message is returned only when the all N subpackets arrive, the retransmission delay becomes large (Fig. 4(b)).

Then, we introduce the threshold α to adjust the timing to return a NACK message. When k subpackets among N transmitting subpackets arrive at a destination node, a NACK message is returned as the following:

1. $k < \alpha$; A NACK message is not returned.
2. $k = \alpha$; A destination node returns a NACK message for α already arrival subpackets, together. This NACK message is transmitted on the route of the first arriving subpacket. After receiving the NACK message, the source node retransmits the α subpackets on the same α routes.
3. $\alpha < k \leq N$; A NACK message for the current received subpacket is returned on the route of the received subpacket. The source node retransmits the subpacket on the same route.

If all N subpackets arrive but errors are detected, the above procedure is repeated until the packet transmission succeeds. Note that the above examples shown in Figs. 4(a) and (b) correspond to the cases of $\alpha = 1$ and $\alpha = 3$, respectively, for $N = 3$. Figure 4(c) shows the example of $\alpha = 2$. By introducing the threshold α, it is possible to adjust retransmission delay and unnecessary subpacket transmissions.

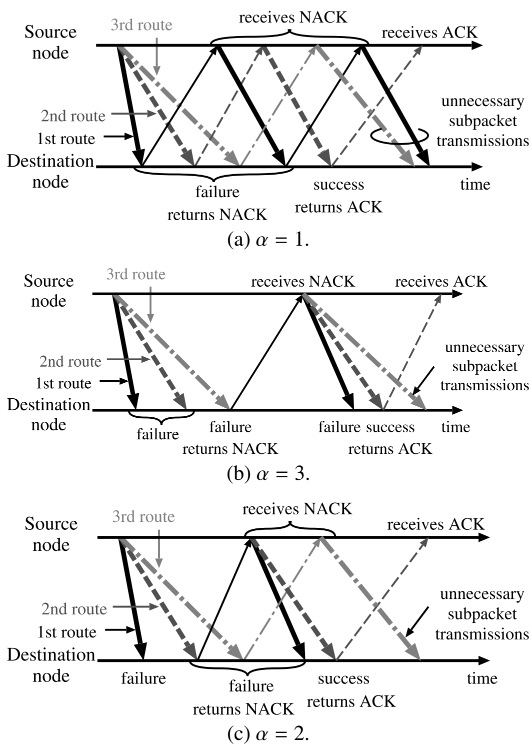


Fig. 4 Examples of various ARQ procedures ($N = 3$).

4. Analysis

4.1 Assumptions and Modeling

At first, we explain assumptions and a queuing network model used in the analysis [8].

An ideal medium access control protocol is assumed, where each node can transmit and receive a subpacket independently, each node is allowed to transmit and receive only one packet simultaneously, every subpacket is received without collisions. For each wireless node, the generation process of transmission requests from all its neighbors is assumed to be modeled as an independent Poisson process with mean λ^{-1}. A packet length is assumed to be exponential with mean $\overline{T}_p = \overline{L}_p/R_b$, where R_b is a transmission rate. Then, a subpacket length is also exponential with mean $\overline{T}_s = \lceil \overline{L}_p/R_c N \rceil / R_b$. According to the assumptions described above, each wireless link is modeled as an M/M/1 queue. The arrival process for each queue corresponds to generations of transmission requests. The service time distribution corresponds to a subpacket length. The time between the generation of a transmission request and the end of its transmission equals waiting time of a queue plus service time of that.

As described in Sect. 2.1, two routes which exist between different source-destination pairs may have common nodes or wireless links. This means that each intermediate node on a route may also be an intermediate node on another route. Therefore, each intermediate node on a route has multiple inputs and multiple outputs. In this case, we can use the independence assumption [11]. With the assumption, the subpacket transmission delay of a route which consists of M_n wireless links is represented by the sum of the waiting times of M_n M/M/1 queues.

The probability density function $f_{\mathbf{w}_1}(t)$ for the subpacket transmission delay $\mathbf{w}_1$ of a wireless link is exponential and given by

$$f_{\mathbf{w}_1}(t) = \mu(1-\rho)e^{-\mu(1-\rho)t}, \tag{1}$$

where $\rho = \lambda/\mu$ is traffic intensity.

Since wireless links on a route are statistically independent and have the same service time distribution, the probability density function $f_{\mathbf{w}_{M_n}}(t)$ for the subpacket transmission delay $\mathbf{w}_{M_n}$ of the M_n-hop route is derived by M_n-fold convolution of (1) and can be expressed as,

$$f_{\mathbf{w}_{M_n}}(t) = \frac{\mu(1-\rho)^{M_n}}{(M_n-1)!} t^{M_n-1} e^{-\mu(1-\rho)t}. \tag{2}$$

The cumulative distribution function $F_{\mathbf{w}_{M_n}}(t)$ for it is also obtained by,

$$F_{\mathbf{w}_{M_n}}(t) = \frac{\Gamma(M_n) - \Gamma(M_n, \mu(1-\rho)t)}{(M_n-1)!}, \tag{3}$$

where $\Gamma(z)$ is the gamma function and $\Gamma(a, z)$ is the incomplete gamma function.

4.2 State Transition for Arrival Process of Subpackets

In order to show the arrival process of subpackets at a destination node, we introduce a trellis diagram $\mathcal{T} = (\mathcal{V}, \mathcal{E})$. Let π_n indicate the nth route and $\mathcal{S}$ be the set of all N routes, that is, $\mathcal{S} = \{\pi_1, \pi_2, \cdots, \pi_N\}$. Then, the trellis $\mathcal{T}$ has the following characters.

1. The node set $\mathcal{V}$ is the power set of $\mathcal{S}$, that is, $\mathcal{V} = 2^{\mathcal{S}}$. Each node means the set of the routes on which subpackets arrive at a destination node.
2. The node set $\mathcal{V}$ is divided into $N+1$ disjoint subsets $\mathcal{V}_j$ ($0 \le j \le N$), that is, $\mathcal{V} = \mathcal{V}_0 \cup \mathcal{V}_1 \cup \cdots \mathcal{V}_N$. The subset $\mathcal{V}_j$ is defined as $\mathcal{V}_j = \{\mathcal{X} \| \mathcal{X}| = j, \mathcal{X} \in \mathcal{V}(= 2^{\mathcal{S}})\}$, where j is equal to the number of subpackets arriving at a destination node. Clearly, $\mathcal{V}_0 = \{\phi\}$ and $\mathcal{V}_N = \{\mathcal{S}\}$. The number of their elements is $|\mathcal{V}_0| = |\mathcal{V}_N| = 1$.
3. The edge set $\mathcal{E}$ is obtained as $\mathcal{E} = \{e(\mathcal{A}, \mathcal{B}) | \mathcal{A} \in \mathcal{V}_{j-1}, \mathcal{B} \in \mathcal{V}_j, A \subset B, 1 \le j \le N\}$. The label $L_{\mathcal{A}}^{\mathcal{B}}$ of the edge $e(\mathcal{A}, \mathcal{B})$ is defined as the element which satisfies the conditions $L_{\mathcal{A}}^{\mathcal{B}} \notin \mathcal{A}$ and $L_{\mathcal{A}}^{\mathcal{B}} \in \mathcal{B}$. The label $L_{\mathcal{A}}^{\mathcal{B}}$ is uniquely decided because $|\mathcal{B} - \mathcal{A}| = 1$. The label $L_{\mathcal{A}}^{\mathcal{B}}$ means the route on which a subpacket newly arrives at a destination node.

The example of the trellis $\mathcal{T}$ for $N = 3$ is shown in Fig. 5. The first state is the node ϕ since no subpackets arrive at a destination node. If a subpacket on the 1st route arrives, the state moves to the node $\{\pi_1\}$. When a subpacket on the 3rd route arrives, the state moves to the node $\{\pi_1, \pi_3\}$. Finally, a subpacket on the 2nd route arrives and the state moves to the

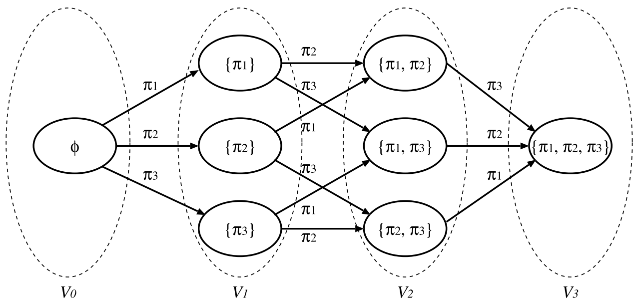


Fig. 5 Trellis diagram for the arrival process of subpackets ($N = 3$).

node $\{\pi_1, \pi_2, \pi_3\}$. The trellis diagram show the all possible arrival process of subpackets.

Furthermore, we introduce the node set $\mathcal{P}(\mathcal{B})$ and $\mathcal{F}(\mathcal{A})$ defined as $\mathcal{P}(\mathcal{B}) = \{\mathcal{A} | \mathcal{A} \in \mathcal{V}_{j-1}, \mathcal{B} \in \mathcal{V}_j, e(\mathcal{A}, \mathcal{B}) \in \mathcal{E})\}$ and $\mathcal{F}(\mathcal{A}) = \{\mathcal{B} | \mathcal{A} \in \mathcal{V}_{j-1}, \mathcal{B} \in \mathcal{V}_j, e(\mathcal{A}, \mathcal{B}) \in \mathcal{E})\}$, respectively. The node set $\mathcal{P}(\mathcal{B})$ means the previous node set of the node $\mathcal{B}$, and the node set $\mathcal{F}(\mathcal{A})$ is the forward node set of the node $\mathcal{A}$.

In the trellis diagram $\mathcal{T}$, we derive the state transition probability $\xi(\mathcal{A}, \mathcal{B})$ from the node $\mathcal{A}$ to the node $\mathcal{B}$, where $B \in \mathcal{F}(\mathcal{A})$. It can be derived by the probability that a subpacket on the route $L_{\mathcal{A}}^{\mathcal{B}}$ arrives next, given that subpackets on the routes $\mathcal{A}$ have arrived. When f_{π_n} and F_{π_n} are the probability density function and the cumulative distribution function for the subpacket transmission delay on the route π_n, respectively, the state transition probability can be expressed as,

$$\xi(\mathcal{A}, \mathcal{B}) = \int_0^\infty f_{L_{\mathcal{A}}^{\mathcal{B}}}(t) \prod_{C \in \mathcal{F}(\mathcal{A}), C \neq \mathcal{B}} (1 - F_{L_{\mathcal{A}}^{C}}(t)) dt. \quad (4)$$

Furthermore, we extend the state transition probability to multistep state transition probability for the case of $\mathcal{A} \subset \mathcal{B}, \mathcal{B} \notin \mathcal{F}(\mathcal{P})$, that is, $|\mathcal{B} - \mathcal{A}| > 1$. Let P_i be the all possible paths from the node $\mathcal{A}$ to the node $\mathcal{B}$. Each path is represented by "P_i: $\mathcal{U}_i^0\ \mathcal{U}_i^1\ \mathcal{U}_i^2 \cdots \mathcal{U}_i^{|\mathcal{B}-\mathcal{A}|}$," where $\mathcal{U}_i^j \in \mathcal{V}_{|\mathcal{A}|+j}$, $\mathcal{U}_i^0 = \mathcal{A}$ and $\mathcal{U}_i^{|\mathcal{B}-\mathcal{A}|} = \mathcal{B}$. Since $\mathcal{U}_i^j$ is the node on the path from $\mathcal{A}$ to $\mathcal{B}$, $\mathcal{U}_i^j$ has to satisfy the conditions, $\mathcal{A} \subset \mathcal{U}_i^j$ and $\mathcal{U}_i^j \subset \mathcal{B}$. Then, the multistep state transition probability may be expressed as,

$$\Xi(\mathcal{A}, \mathcal{B}) = \sum_{\mathrm{P}_i} \prod_{j=0}^{|\mathcal{B}-\mathcal{A}|-1} \xi(\mathcal{U}_i^j, \mathcal{U}_i^{j+1}). \quad (5)$$

The state inverse transition probability $\zeta(\mathcal{B}, \mathcal{A})$ is defined as the probability that a subpacket on the route $L_{\mathcal{A}}^{\mathcal{B}}$ is the last one to arrive among routes $\mathcal{B}$, given that the ending state is $\mathcal{B}$, where $\mathcal{A} \in \mathcal{P}(\mathcal{B})$. It can be derived by,

$$\zeta(\mathcal{B}, \mathcal{A}) = \int_0^\infty f_{L_{\mathcal{A}}^{\mathcal{B}}}(t) \prod_{C \in \mathcal{P}(\mathcal{B}), C \neq \mathcal{A}} (1 - F_{L_{C}^{\mathcal{B}}}(t)) dt. \quad (6)$$

Let $P_e(\mathcal{X})$ be the packet error rate when subpackets on the routes $\mathcal{X}$ arrive at a destination node. For example, if $\mathcal{X} = \{\pi_1, \pi_2\}$, $P_e(\mathcal{X})$ is the packet error rate when subpackets on the 1st and 2nd routes arrive. The cumulative packet success rate $P_{cs}(\mathcal{X})$ is defined as the sum of packet success rates for all possible route subsets of $\mathcal{X}$. For the above example, $P_{cs}(\mathcal{X})$ is the packet success rate when a subpacket on the 1st route arrives, a subpacket on the 2nd route arrives, or subpackets on the 1st and 2nd routes arrive. Due to a mutual exclusive event, $P_{cs}(\mathcal{X}) = 1 - P_e(\mathcal{X})$.

The termination probability $\Pi(\mathcal{X})$ is defined as the probability that the arrival process of subpackets is finished at the node $\mathcal{X}$ since the packet transmission succeeds. Obviously, $\Pi(\phi) = 0$. Furthermore, $\sum_{\mathcal{X} \in \mathcal{V}} \Pi(\mathcal{X}) = P_{cs}(\mathcal{S})$.

When $C \in \mathcal{V}_j$ $(1 \le j \le N)$, the cumulative packet success rate $P_{cs}(C)$ has to be larger than $P_{cs}(\mathcal{B})$ $(\mathcal{B} \in \mathcal{P}(C))$ since a subpacket on the route $L_{\mathcal{B}}^{C}$ newly arrives at a destination node. Then, the packet success rate when a subpacket on the route $L_{\mathcal{B}}^{C}$ arrives next, given that subpackets on the routes $\mathcal{B}$ have arrived, is derived as $P_{cs}(C) - P_{cs}(\mathcal{B}) = P_e(\mathcal{B}) - P_e(C)$. Considering the possible state transitions, the termination probability $\Pi(C)$ can be expressed as,

$$\Pi(C) = \sum_{\mathcal{B} \in \mathcal{P}(C)} \beta(\mathcal{B}) \xi(\mathcal{B}, C) \{P_e(\mathcal{B}) - P_e(C)\}, \quad (7)$$

where $\beta(\mathcal{B})$ is defined as,

$$\beta(\mathcal{B}) = \begin{cases} 1 & (\text{if } \mathcal{B} = \phi) \\ \sum_{\mathcal{A} \in \mathcal{P}(\mathcal{B})} \beta(\mathcal{A}) \xi(\mathcal{A}, \mathcal{B}) & (\text{otherwise}) \end{cases}. \quad (8)$$

4.3 Total Number of Subpacket Transmissions and Traffic Intensity

In this section, the total number of subpacket transmissions is derived by using the termination probability. By using the total number, the traffic intensity is also obtained.

Let $\kappa_s(i, j)$ and $\kappa_a(i, j)$ be the total subpacket transmissions and total ACK/NACK transmissions, respectively, of the case that the packet transmission succeeds when j subpackets of the ith (re)transmission arrive. If the packet transmission succeeds when the number of arrival subpackets is equal to or less than the threshold α, a NACK message is not returned. So the number of total subpacket transmissions is $i \cdot N$. The total number of NACK and transmissions is $(i-1)(N-\alpha+1)+1$. Otherwise, $(j-\alpha)$ NACK messages are returned and $(j-1)$ unnecessary subpackets are retransmitted. Therefore, the total subpacket transmissions $\kappa_s(i, j)$ is derived by,

$$\kappa_s(i, j) = \begin{cases} i \cdot N & (j \le \alpha) \\ i \cdot N + (j-1) & (j > \alpha) \end{cases}. \quad (9)$$

The total ACK/NACK transmissions $\kappa_a(i, j)$ is obtained by,

$$\kappa_a(i, j) = \begin{cases} (i-1) \cdot (N-\alpha+1) + 1 & (j \le \alpha) \\ (i-1) \cdot (N-\alpha+1) & \\ \quad + (j-\alpha) + 1 & (j > \alpha) \end{cases}. \quad (10)$$

By using the termination probability, the average amount of total subpacket and ACK/NACK transmissions may be expressed as,

$$\overline{\kappa} = \sum_{i=1}^{\infty}\sum_{j=1}^{N}\sum_{\mathcal{X}\in\mathcal{V}_j}(\kappa_s(i,j) + R_a\kappa_a(i,j))$$
$$\cdot\Pi(\mathcal{X})P_e(\mathcal{S})^{i-1}, \tag{11}$$

where $R_a = \overline{T_a}/\overline{T_s}$ is the time ratio of the average ACK/NACK message length $\overline{T}_a = \overline{L}_a/R_b$ to the subpacket length.

The base traffic intensity ρ_0 is defined as the traffic generation intensity of transmission requests, that is, $\rho_0 = \lambda_0\overline{T}_p$, where λ_0 is the birth rate of transmission requests. The traffic intensity ρ of each wireless link increases in proportion to the average amount of total subpacket and ACK/NACK transmissions. Then, the traffic intensity may be expressed as,

$$\rho = \lambda\cdot\mu^{-1} \approx \overline{\kappa}\lambda_0\cdot\frac{\overline{T}_p}{R_cN} = \frac{\overline{\kappa}\rho_0}{R_cN}. \tag{12}$$

4.4 Delay and Throughput Analysis

At first, let us consider the case when subpackets on the routes $\mathcal{S}'(\subset\mathcal{S})$ are sent at the same time by a source node. The trellis diagram of this case is denoted by $\mathcal{T}'$. In this case, we define $\mathbf{w}_{(\mathcal{S}',\mathcal{B}')}$ as the transmission delay time when subpackets on the routes $\mathcal{B}'$ arrive at a destination node and those on the route $(\mathcal{S}'-\mathcal{B}')$ do not arrive. By considering the previous node set $\mathcal{P}'(\mathcal{B}')$ of the node $\mathcal{B}'$, the probability density function of $\mathbf{w}_{(\mathcal{S}',\mathcal{B}')}$ is derived by

$$f_{\mathbf{w}_{(\mathcal{S}',\mathcal{B}')}}(t) = \sum_{\mathcal{A}'\in\mathcal{P}'(\mathcal{B}')}$$
$$\left\{\prod_{\pi_n\in\mathcal{A}'}F_{\pi_n}(t)\prod_{\pi_n\in\mathcal{X}'}(1-F_{\pi_n}(t))f_{L^{\mathcal{B}'}_{\mathcal{A}'}}(t)\right\}, \tag{13}$$

where $\mathcal{X}' = \mathcal{S}' - \mathcal{A}' - \{L^{\mathcal{B}'}_{\mathcal{A}'}\}$. Then, the average delay time of $\mathbf{w}_{(\mathcal{S}',\mathcal{B}')}$ is obtained by

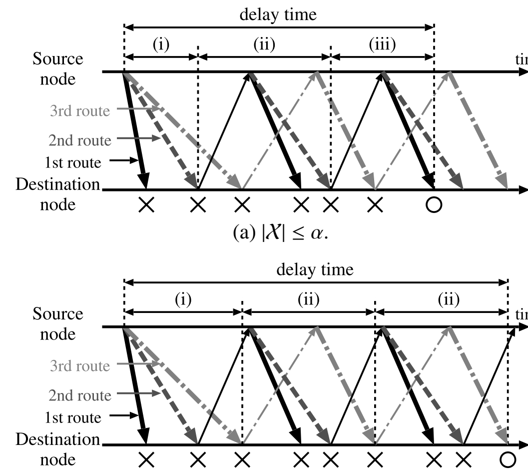
$$d(\mathcal{S}',\mathcal{B}') = \int_0^{\infty} t\cdot f_{\mathbf{w}_{(\mathcal{S}',\mathcal{B}')}}(t)dt. \tag{14}$$

The average delay time when subpackets on the routes $\mathcal{X}$ of the ith transmission arrive, $D_{i,\mathcal{X}}$, is derived as the following.

1. $|\mathcal{X}| \le \alpha$; In this case, we consider two situations. One situation is $i = 1$. The delay time of this situation can be easily obtained by,

$$D_{1,\mathcal{X}} = d(\mathcal{S},\mathcal{X}). \tag{15a}$$

The other situation is $i > 1$. The delay time analysis of this situation is complicated. An example of retransmission process is shown in Fig. 6(a). We derive the delay time by dividing it into 3 parts. (i) The first part is the delay time until return of the first NACK. It corresponds to the delay time from transmissions of N subpackets at a source node to arrivals of α subpackets at a destination node. (ii) The second part is the retransmission delay time if the packet transmission does not succeed. We assume a NACK message is returned on the first arrival route. Then, the delay time of the second part is the transmission delay of a NACK message plus the delay time from transmissions of α subpackets to arrivals of α subpackets. (iii) The third part is the retransmission delay time just before the successful transmission. It is the transmission delay of a NACK message plus the delay time from transmissions of α subpackets to the successful packet transmission. Therefore, the delay time can be obtained by,



(a) $|\mathcal{X}| \le \alpha$.

(b) $|\mathcal{X}| > \alpha$.

Fig. 6 Retransmission process and delay time ($N = 3, \alpha = 2$).

$$D_{i,\mathcal{X}} = \sum_{\mathcal{B}\supset\mathcal{X},|\mathcal{B}|=\alpha}\Xi(\mathcal{X},\mathcal{B})\Big[d(\mathcal{S},\mathcal{B})$$
$$+\sum_{\mathcal{A}\in\mathcal{V}_1,\mathcal{A}\subset\mathcal{B}}\xi(\{\phi\},\mathcal{A})\{(d(\mathcal{A},\mathcal{A}) + d(\mathcal{B},\mathcal{B}))(i-2)$$
$$+d(\mathcal{A},\mathcal{A}) + d(\mathcal{B},\mathcal{X})\}\Big]. \tag{15b}$$

2. $|\mathcal{X}| > \alpha$; In this case, the delay time is divided into 2 parts, as shown in Fig. 6(b). (i) The first part is the delay time from the first transmission of N subpackets to arrivals of subpackets on the routes $\mathcal{X}$. (ii) The second part is the retransmission delay time. It is the transmission delay of a NACK message plus its retransmitted subpacket. Then, the delay time may be expressed as,

$$D_{i,\mathcal{X}} = d(\mathcal{S},\mathcal{X}) + 2\sum_{\mathcal{A}\in\mathcal{P}(\mathcal{X})}\zeta(\mathcal{X},\mathcal{A})$$
$$\cdot d(\{L^{\mathcal{X}}_{\mathcal{A}}\},\{L^{\mathcal{X}}_{\mathcal{A}}\})(i-1). \tag{15c}$$

By using $D_{i,\mathcal{X}}$, the total average delay time can be derived by,

$$\overline{D} = \sum_{i=1}^{\infty}\sum_{\mathcal{X}\in\mathcal{V}-\{\phi\}}D_{i,\mathcal{X}}\Pi(\mathcal{X})P_e(\mathcal{S})^{i-1}. \tag{16}$$

The throughput is defined as the time ratio of a packet transmission to the elapsed time until its successful transmission in each wireless link. It is obtained by

$$S = \frac{\overline{T_p}}{\overline{D}/\overline{M}}, \tag{17}$$

where $\overline{M}$ is the average number of hops, derived by $\overline{M} = 1/N \sum_{n=1}^{N} M_n$.

4.5 Simplification of Analysis

In this section, we consider the simplified network and wireless link model. It restricts the narrow application of the analysis, but it is enough to investigate the essential property of the proposed source-destination ARQ.

If the subpacket transmission delay on each route is independent identically distributed (iid), the state transition probability $\xi(\mathcal{A}, \mathcal{B})$ can be simplified. This assumption is available when the number of hops is identical among all routes ($M_n = M$) and traffic intensity is uniformly distributed. Under this assumption, the state transition probability $\xi(\mathcal{A}, \mathcal{B})$ is identical among the node set $\mathcal{F}(\mathcal{A})$, that is, $\xi(\mathcal{A}, \mathcal{B}) = 1/|\mathcal{F}(\mathcal{A})|$. The detail of this derivation is described in Appendix.

Let $\mathbf{w}_{(n,j)}$ be defined as the elapsed time of j subpacket arrivals at a destination node when n subpackets are sent by a source node. Then, the probability density function of $\mathbf{w}_{(n,j)}$ is derived by

$$f_{\mathbf{w}_{(n,j)}}(t) = \frac{n!}{(j-1)!(n-j)!} \cdot F_{\mathbf{w}_M}{}^{j-1}(t)\{1 - F_{\mathbf{w}_M}(t)\}^{n-j} f_{\mathbf{w}_M}(t). \tag{18}$$

Therefore, the average delay time of $\mathbf{w}_{(n,j)}$ is obtained by

$$d(n, j) = \int_0^{\infty} t \cdot f_{\mathbf{w}_{(n,j)}}(t) dt. \tag{19}$$

When $n = j = 1$, $d(n, j)$ can be simply expressed as,

$$d(1, 1) = \frac{1}{\mu(1-\rho)} M. \tag{20}$$

By using $d(n, j)$, the average delay time when j subpackets of the ith transmission arrive is derived as the following:

1. $j \le \alpha$;

$$D_{i,j} = \begin{cases} d(N, j) & (i = 1) \\ d(N, \alpha) \\ \quad +\{d(1,1) + d(\alpha, \alpha)\}(i-2) \\ \quad +d(1,1) + d(\alpha, j) & (i > 1) \end{cases} \tag{21a}$$

2. $j > \alpha$;

$$D_{i,j} = d(N, j) + 2d(1, 1)(i-1). \tag{21b}$$

Then, the total average delay time may be expressed as,

$$\overline{D} = \sum_{i=1}^{\infty} \sum_{j=1}^{N} \sum_{\mathcal{X} \in \mathcal{V}_j} D_{i,j} \Pi(\mathcal{X}) P_e(\mathcal{S})^{i-1}. \tag{22}$$

The throughput is obtained by (17).

If the statistical character of each wireless link is assumed as iid process, the derived equations can be further simplified. In the iid wireless link model, the packet error rate of the nodes $\mathcal{X} \in \mathcal{V}_j$ is identical. If this packet error rate is denoted as $P_e(\mathcal{V}_j)$, (7), (11) and (22) may be rewritten by,

$$\Pi(\mathcal{V}_j) = P_e(\mathcal{V}_{j-1}) - P_e(\mathcal{V}_j), \tag{23}$$

$$\overline{\kappa} = \sum_{i=1}^{\infty} \sum_{j=1}^{N} (\kappa_s(i, j) + R_a \kappa_a(i, j)) \cdot \Pi(\mathcal{V}_j) P_e(\mathcal{S})^{i-1}, \tag{24}$$

and

$$\overline{D} = \sum_{i=1}^{\infty} \sum_{j=1}^{N} D_{i,j} \Pi(\mathcal{V}_j) P_e(\mathcal{S})^{i-1}. \tag{25}$$

5. Numerical Results

In this section, we evaluate the proposed ARQ scheme in two cases. One is the simplified network and wireless link model, described in Sect. 4.5. The other is the practical model in which the Multipath Dynamic Source Routing (MDSR) [12] is employed to establish multiple routes. This model supposes an application to 2.4 GHz wireless LAN multihop networks.

In the following discussions, the overhead of NACK/ACK messages is considered as described in Sect. 4.3, but that of packet header and routing protocol due to multiple route transmission is ignored because its degradation will be small.

5.1 Case of Simplified Network and Wireless Link Model

The packet error rate $P_e(\mathcal{V}_j)$ is obtained by Monte Carlo simulation. The operating parameters are shown in Table 1. The turbo code is employed as an error correcting code with a rate 1/3. The Rayleigh fading environment is assumed on each wireless link. The fading loss is constant during a subpacket transmission, and independently varies at each subpacket (re)transmission, each wireless link. For comparison, the performance of a single route transmission is also shown. In this case, the rate compatible punctured turbo

Table 1 Simulation parameters for the case of simplified network and wireless link model.

average packet length $\overline{L_p}$	1,000 bits
average ACK/NACK length $\overline{L_a}$	100 bits
error detecting code	ideal
error correcting code	turbo code with a rate 1/3, (37,21) RSCs, SOVA decoder, number of iteration is 5
modulation scheme	BPSK
wireless link model	Rayleigh fading
the number of routes N	3
the number of hops M	3

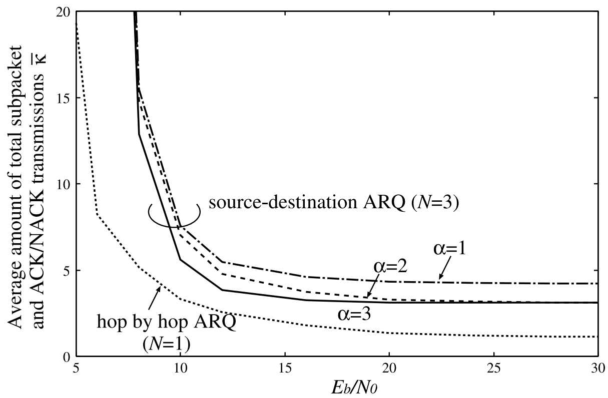


Fig. 7 Average amount of total subpacket and ACK/NACK transmissions versus E_b/N_0 for the case of simplified network and wireless link model.

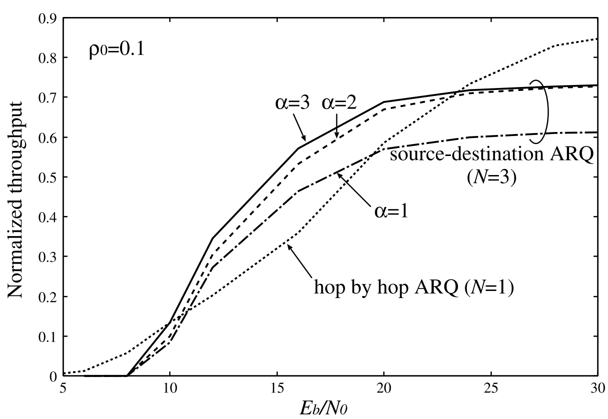


Fig. 8 Normalized throughput versus E_b/N_0 for the case of simplified network and wireless link model.

(RCPT) ARQ with a puncturing period $P = 2$ [13] is performed at hop by hop.

The average amount of total subpacket and ACK/NACK transmissions versus E_b/N_0 is shown in Fig. 7, where E_b is bit energy and $N_0/2$ is two side power spectral density. The minimum value of the average amount comes close to 1 for the case of the hop by hop ARQ with $N = 1$. For the case of the source-destination ARQ with $N = 3$, the minimum value converges at 3 except for $\alpha = 1$. However, it becomes 4 for $\alpha = 1$. It is because 2 or more subpackets are required for the successful decoding. Then, an unnecessary subpacket transmission occurs for $\alpha = 1$.

Figure 8 shows the throughput normalized by the average packet length versus E_b/N_0 for $\rho_0 = 0.1$. The normalized throughput corresponds to the end-to-end efficiency. If the maximum throughput from the source node to the destination node is 1 Mbps, for example, its effective throughput becomes 1× (normalized throughput) Mbps. Large average number of total subpacket transmissions brings about an increase in the traffic and degradation of the throughput. When E_b/N_0 is below 10 dB, the average number of total subpacket transmissions becomes very large. So the throughput is unacceptably low. The throughput of the source-destination ARQ is better than that of the hop by hop ARQ when E_b/N_0 becomes larger. But for much larger E_b/N_0, the best throughput is obtained by the hop by hop ARQ. It is because the packet error rate is pretty good and to reduce the number of subpacket transmissions is the dominant factor to increase the throughput.

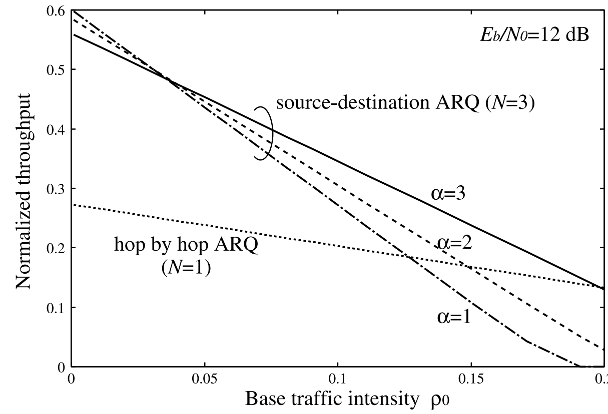


Fig. 9 Normalized throughput versus base traffic intensity ρ_0 for the case of simplified network and wireless link model.

Table 2 Simulation parameters for the case of multipath dynamic source routing.

area	1,000 m×1,000 m
number of nodes	300
distribution of nodes	uniform
distance from source node to destination node	500 m
path loss exponent	3.5 (received SNR=15 dB at distance 100 m)
standard deviation of lognormal shadowing	7 dB
required SNR	12 dB

Figure 9 shows the normalized throughput versus base traffic intensity for $E_b/N_0 = 12$ dB. For the low base traffic intensity, the throughput of the source-destination ARQ is better than that of the hop by hop ARQ because the hop by hop ARQ increases the delay and it results in the throughput degradation. However, the source-destination ARQ increases the traffic due to multiple subpacket transmissions. So the throughput is degraded for the high base traffic intensity. Furthermore, the throughput for $\alpha = 1$ is the best performance for the low base traffic intensity because of the reduction of delay. On the other hand, the highest throughput can be obtained for $\alpha = 3$ for the high base traffic intensity since unnecessary subpacket transmissions are prevented.

5.2 Case of Multipath Dynamic Source Routing

In this section, we employ the MDSR [12] to establish multiple routes. The MDSR is based on the Dynamic Source Routing (DSR) protocol.

Table 2 shows the simulation parameters. There are 300 nodes distributed uniformly in 1,000 m × 1,000 m area. The distance from a source node to a destination is fixed at 500 m. In wireless links, distance dependent path loss, lognormal shadowing, and flat Rayleigh fading are considered. The transmission power is identical among all nodes. The path loss exponent is set at 3.5, and the received SNR at a distance 100 m is 15 dB if only distance dependent path loss is considered. The lognormal shadowing loss is constant while its wireless link is held. We define link connectivity SNR as received SNR affected by distance dependent path loss and lognormal shadowing. Wireless links are available if link connectivity SNR is above required SNR. The fading gain is constant during a subpacket transmission and varies at each subpacket transmission. The occurrence of bit errors in each wireless link depends on instantaneous SNR, which considers the effect of distance dependent path loss, shadowing and fading. Similar to Sect. 5.1, the fading loss is constant during a subpacket transmission, and independently varies at each subpacket (re)transmission. The average packet length, error detecting and correcting codes, modulation scheme are the same with Table 1.

Table 3 shows the average number of total subpacket transmissions normalized by R_cN, which corresponds to the bit ratio of total transmitted subpackets to a packet. The normalized average number decreases by increasing the number of transmit routes because larger diversity gain can be obtained. It also decreases by increasing the threshold α since unnecessary subpacket transmissions are restrained. However, the increase in the threshold α results in the increase in the retransmission delay.

Figure 10 shows the throughput normalized by a packet length. For the low base traffic intensity, higher throughput is obtained by decreasing the threshold α due to shorter retransmission delay. On the other hand, to restrain unnecessary subpacket transmissions is effective for the high base traffic intensity. Therefore, the increase in the threshold α brings about the throughput improvement. Compared with the curves in Fig. 9, almost the same feature is seen although the absolute value is slightly better. Then the simplified network and wireless link model can be used to investigate the performance of the proposed scheme.

Table 3 Average amount of total subpacket and ACK/NACK transmissions for the MDSR case.

number of routes N	threshold α	normalized average amount of total subpacket & ACK/NACK transmissions $\overline{\kappa}/R_cN$
3	1	4.73
	2	3.92
	3	3.30
6	2	4.90
	4	3.88
	6	3.12

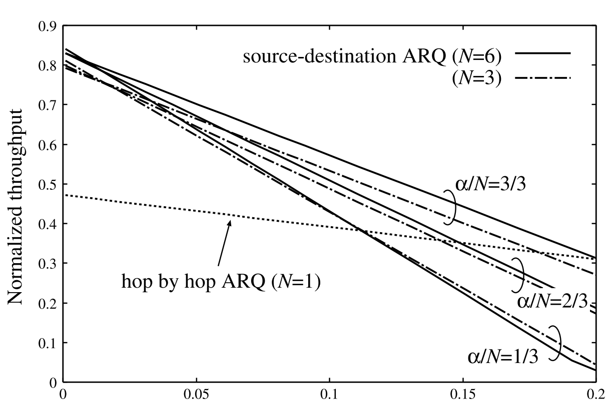


Fig. 10 Normalized throughput versus base traffic intensity for the case of MDSR.

6. Conclusions

In this paper, we have proposed the source-destination ARQ scheme for the multiroute coding scheme in wireless multihop networks. To reduce delay, a destination node decodes and error-detects subpackets every time a subpacket arrives. Furthermore, we have introduced the threshold to adjust the timing to return a NACK message.

By introducing the queueing model and trellis diagram, we have analyzed the proposed source-destination ARQ scheme. We have evaluated the system performance in the two cases. As a result, we have clarified that the proposed ARQ scheme can achieve the good throughput performance, specially for the low traffic intensity. The adjustment of the threshold by estimating the traffic intensity could optimize the throughput performance in the proposed ARQ scheme.

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Appendix

For the case of iid subpacket transmission delay model, the state transition probability (4) can be simplified. Under this assumption, the probability density function and cumulative distribution function of the subpacket transmission delay is identical among all routes. Therefore, (4) becomes,

$$\xi(\mathcal{A},\mathcal{B}) = \int_0^\infty f_{L_\mathcal{A}^\mathcal{B}}(t) \prod_{\mathcal{C}\in\mathcal{F}(\mathcal{A}),\mathcal{C}\neq\mathcal{B}} (1 - F_{L_\mathcal{A}^\mathcal{C}}(t))dt = \int_0^\infty f_{\mathbf{w}_M}(t)(1 - F_{\mathbf{w}_M}(t))^{|\mathcal{F}(\mathcal{A})|-1}dt. \quad \text{(A}\cdot\text{1)}$$

From the binomial theorem, (A· 1) can be rewritten by,

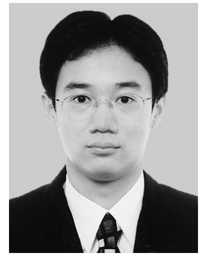
$$\begin{aligned}\xi(\mathcal{A},\mathcal{B}) &= \int_0^\infty f_{\mathbf{w}_M}(t) \sum_{i=0}^{|\mathcal{F}(\mathcal{A})|-1} \binom{|\mathcal{F}(\mathcal{A})|-1}{i} \cdot(-1)^i F^i_{\mathbf{w}_M}(t)dt \\ &= \sum_{i=0}^{|\mathcal{F}(\mathcal{A})|-1} \binom{|\mathcal{F}(\mathcal{A})|-1}{i}(-1)^i \cdot \int_0^\infty f_{\mathbf{w}_M}(t)F^i_{\mathbf{w}_M}(t)dt. \quad \text{(A}\cdot\text{2)}\end{aligned}$$

Since $dF_{\mathbf{w}_M}(t)/dt = f_{\mathbf{w}_M}(t)$,

$$\int_0^\infty f_{\mathbf{w}_M}(t)F^i_{\mathbf{w}_M}(t)dt = \frac{1}{i+1}\left[F^{i+1}_{\mathbf{w}_M}(t)\right]_0^\infty = \frac{1}{i+1}. \quad \text{(A}\cdot\text{3)}$$

From (A· 3), (A· 2) becomes

$$\xi(\mathcal{A},\mathcal{B}) = \sum_{i=0}^{|\mathcal{F}(\mathcal{A})|-1} \binom{|\mathcal{F}(\mathcal{A})|-1}{i}(-1)^i \frac{1}{i+1} = \frac{1}{|\mathcal{F}(\mathcal{A})|}. \quad \text{(A}\cdot\text{4)}$$



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